THE ELASTIC PROPERTIES OF THE ARTERIAL WALL.

BY CHARLES S. ROY, M.D., *George Henry Lewes Student.*

Pl. V., VI., VII.

(*From Experiments made in part in the Strassburg Physiological Institute.*)

HAVING found it desirable, in the course of some investigations on the form of the pulse-wave, to elucidate one or two points connected with the elasticity of the arteries, I was led to undertake a number of experiments on the subject. These observations have become more extended than was at first contemplated, so much so that I consider it advisable to describe in a separate communication the results at which I have arrived.

At first I sought only to determine, by direct experiment, what is the relation which exists between the intra-arterial pressure and the cubic capacity of any given portion of artery. In the course of my work on this subject, however, a number of facts came under my notice which seemed to deserve further investigation, and I was thus led to widen the limits of my experiments.

I. Elasticity of Animal Tissues in general.

Amongst those physical properties of the walls of the arteries which came to light in the course of this research, some, as might have been expected, were found to characterize other animal tissues as well, and to one or two of these I would call attention before treating of those attributes of the elasticity of the arterial wall which are peculiar to it, and which, apparently, are intimately bound up with its function in the animal economy.

It is now pretty generally accepted that, in one important particular at least, the elastic properties of moist inorganic substances are markedly different from those of metals, glass, dry wood, &c. In the case of these latter the law of Hooke, *ut tensio sic vis*, is still held to be practically correct; within certain limits the elongations produced by weights are proportionate to the weights employed.

With animal tissues (excepting bone) this law does not hold good. The increments in length, produced by the addition of successively increasing weights, diminish gradually in proportion to the weights employed. The curve of longitudinal elasticity (for example, of a portion of voluntary muscle or a strip of skin), constructed by taking the weights used to elongate the piece of tissue as the abscissæ, the elongations being taken as the ordinates, is, as was first shown by Werthheim[1], a curve which is concave towards the abscissa line, and which bears a certain resemblance to a hyperbola. With a metallic wire, on the other hand, the curve constructed in a similar manner is at first more or less perfectly straight.

This difference in the behaviour of animal tissues as compared with metals cannot be explained, as was attempted by Wundt[2], by ascribing it to the employment, in the case of experiments on animal tissues, of too great a range in the value of the weights employed, combined with a faulty method of inquiry.

When we examine the matter a little more closely we find, moreover, that the difference in the longitudinal elasticity of metals, as compared with that of animal tissues, is still greater than it appears at first sight. For many metals, at least, the curve of elasticity, constructed in the above-mentioned manner, is only within comparatively narrow limits a straight line, and on its ceasing to be straight the convexity of the bend which it takes is turned towards the abscissa line, giving therefore an entirely different form of curve from that found in the case of animal tissues. It is only with still further increase in the weights employed, and long after the so-called limit of elasticity has been passed, and the breaking point is approached, that the curve of these metals comes to resemble that of animal tissues in so far that the concavity is turned towards the abscissa.

There is, then, a very striking difference in the longitudinal elasticity curve of animal tissues and that of metals. So striking, indeed, is this difference that we might reasonably anticipate that it would be accompanied by other distinctive peculiarities in the physical characteristics of the two sets of substances. And such is, in reality, the case.

I. *Thermo-elastic properties of Animal Tissues.*

Various considerations having led me to doubt whether animal tissues follow the ordinary rule as to the relation which exists between the

[1] Werthheim. *Ann. de Chim. et Phys.* (3), XII., p. 385, 581, 610, 1841; and XXI., p. 385, 1847.

[2] Wundt. *Verhl. d. Naturh.-med. Ver. zu Heidelberg*, I., S. 2, 1856; also in *Die Lehre von der Muskelbewegung*.

temperature of the tissue and its passive expansion or contraction, I made a number of experiments with the view of determining—

1st. Whether, when a portion of artery, skin, &c., is stretched, its temperature rises or falls; and 2nd. Whether, when a portion of animal tissue is warmed, it expands or contracts.

a. Changes of temperature produced by expansion and relaxation.

As is well known, when a metal is compressed it becomes warmer, and when a metallic wire, for example, is stretched it becomes colder: and this rule has, excepting in the case of one or two substances, been found universal. The most familiar exception is caoutchouc, which becomes warmer on being stretched and cools on contracting again.

In my experiments on the behaviour of animal tissues in this respect the following was the method employed:—

A strip of the tissue to be examined was hung up in such a way that it could be stretched at will by means of weights, while a sensitive thermopile was gently pressed against its surface.

The necessary instruments I found ready to hand in Prof. Goltz's institute. The galvanometer employed was that of Magnus, while for a thermopile I made use of one which had been constructed for experiments on radiant heat, and which I found more than sufficiently delicate for this particular kind of work. Heidenhain's thermopile was also occasionally employed, the arrangement of its holder being found very convenient. When this latter was not made use of, the pile was held pressed against the tissue, either by a couple of pins, or more exact apposition was effected by means of a small pad of cotton wool, between which and the face of the pile, by means of india-rubber thread, the strip of tissue was gently compressed. The pile was so suspended by threads that it readily followed the downward movement of the tissue on the latter being stretched.

Since it was evident that stretching the tissue would diminish the extent of its surface which was covered by the pile, and that thereby the area from which evaporation could take place would be correspondingly increased, it seemed necessary to exclude by control experiments any error which might thus be introduced. By covering the strip of tissue and part of the thermopile with oil all evaporation from the former could be prevented; and a number of experiments were made in this way, which, however, gave the same results as those in which no special means were taken to prevent evaporation.

It is scarcely necessary to enter further into the details of the method employed in making these experiments.

The result for all the tissues examined, viz., arterial and venous wall, skin, nerve, tendon and muscle, was the same.

Their temperature rises on their being stretched, and falls on their being again relaxed. Whether light or heavy weights are employed, the result is the same. The degree of movement of the needle was found to increase in direct proportion (speaking roughly) to the weights employed.

Circumstances did not permit me to measure exactly the rise of temperature caused by the application of given weights to a portion of tissue having a given sectional area, even had the subject appeared of sufficient importance, from a physiological point of view, to warrant the undertaking of experiments requiring so much time and trouble.

Since making these experiments I have found that Westermann had already observed that muscle on being stretched becomes warmer, but he does not appear to have examined the behaviour of other animal tissues in this respect.

b. Effect of variations of temperature on the length of portions of animal tissues.

According to the thermo-dynamic theory enunciated by Sir W. Thomson[1], it is concluded "that cold is produced whenever a solid is strained by opposing, and heat when it is strained by yielding to, any elastic force of its own, the strength of which would diminish if the temperature were raised; but that, on the contrary, heat is produced when a solid is strained against, and cold when it is strained by yielding to, any elastic force of its own, the strength of which would increase if the temperature were raised."

Reasoning from the converse of this theory, we should expect that, since animal tissues become warmer on being stretched, they will also differ from other substances in that they will contract on their temperature being raised. This point appeared to me of sufficient interest to deserve investigation.

The method employed was the following:—A long, narrow trough, fixed firmly within a larger one, contained the piece of tissue. The inner compartment of this double trough measured 20 cm. long by 5 broad, its depth being 7 cm. In this the strip of tissue, firmly clamped

[1] "Thermo-elastic properties of matter." *Quarterly Journal of Mathematics*, April, 1857.

at both ends, was placed, after which olive oil, sufficient in quantity to cover it, was poured in. The temperature of the oil could be learned by means of a thermometer, while, in the outer compartment of the double trough, warm or cold water was poured, according to the degree of heat which it was desired to impart to the oil, and, with it, to the strip of tissue. The variations in the length of the latter were recorded by a long lever connected with the tissue in the following manner :—

At one end of the interior of the trough was a strong peg on which one clamp was hooked, while at the other end was a small pulley, round which passed a strong silk thread attached to the other clamp. The thread passed upwards out of the oil, and, after making two or three turns round a pin fixed in the side of the recording lever near its axis of rotation, was carried over a large pulley placed above the lever. To the end of the thread was attached a scale for weights.

With this arrangement, then, the temperature of the tissue could be varied at will, while any corresponding variations in its length were magnified by means of the lever. No evaporation from the surface of the strip of tissue could take place; its condition as to moisture remained, therefore, unchanged during the experiment.

For these observations I made use of strips, 1 cm. in breadth, taken from the human aorta, and also from the aorta of the cow and sheep. I did not consider it necessary to examine any other tissue in this respect, believing that, under the circumstances, the results obtained might safely be held applicable to all animal tissues. I give the notes of two of these experiments which will illustrate sufficiently the nature of the results arrived at.

Exp. 4.—Strip of human aorta, taken in the direction of the length of the vessel. Breadth of strip = 1 cm. From subject of 17 years of age.

Length of strip unstretched = 9·25 cm. Stretched by means of weights to length of 12·2 c.m.

Time.	Temp. of Oil in degrees of Celsius.	Length of Strip.
2.40 p.m.	19·4	12·25 cm.
2.52 „	32·5	12·14 „
3.5 „	44·1	12·02 „
3.25 „	54·1	11·96 „
3.50 „	19·0	12·24 „

Exp. 6.—Strip of human aorta, 1 cm. broad, taken transversely. Length when stretched by weight of 50 grammes = 8·32 cm.

Time.	Temperature.	Length.
2.55 p.m.	16·5	8·32
3.15 „	22·0	8·256
3.35 „	25·0	8·205
4.0 „	30·0	8·155
4.20 „	40·0	8·099
5.0 „	17·5	8·295

Animal tissues must, then, be classed along with caoutchouc and bismuth, as exceptions to the general rule that heat causes expansion and cold contraction. They also, in accordance with the thermo-dynamic theory of Thomson, become warmer on being stretched and colder on being again relaxed. I shall have occasion to return to the thermo-elastic properties of animal tissues in considering the form of the curve of longitudinal elasticity of the arterial wall.

II. *Viscosity*[1] *of Animal Tissues*[2].

In experiments on the longitudinal elasticity of animal tissues care must constantly be taken that error is not introduced owing to the disturbing influence of the elasticity after-action (*elastische Nachwirkung*). This phenomenon, which was first investigated by E. Weber[3], consists, as is well known, in a secondary gradual expansion or contraction, lasting, it may be, for hours or even days after the primary expansion or contraction. When, for example, a strip of arterial wall, hung up by one extremity is stretched, by means of weights attached to its lower end, it does not at once attain the full degree of expansion which will finally be produced by the weight employed, but, after having stretched rapidly to a certain length, it continues gradually and

[1] I see no reason why the term "viscosity," should not be applied to the molecular friction, or internal resistance, which must be looked upon as the cause of the after-action. The after-action is a phenomenon, and not a property, and some word is required which can express conveniently the causal molecular condition. Should further investigations show that the viscosity of metals, discovered by Thomson, is something essentially different in nature from the viscosity which causes the after-action, it will then be time enough to give the latter a distinctive name.

[2] I have not made any connected series of experiments on this subject, and by rights it should not be referred to at length in a communication of this kind. I have, however, thought it advisable to say something on the subject, because, so far as I know, nothing is contained in English physiological literature concerning the elasticity after-action.

[3] Poggendorf's *Annalen*, 1841.

with increasing slowness to elongate, until a point is reached at which the elasticity of the tissue exactly balances the weight used, and the two opposing forces are in equilibrium. This after-expansion, which cannot be sharply distinguished from the primary expansion, since the latter passes insensibly into the former, does not arise from a change in the elasticity of the piece of tissue examined, since that the latter returns more or less exactly to its former length on the expanding weights being removed. In this latter case the shortening occurs in the same manner as did the expansion, *i.e.*, on removing the weights, the strip of tissue contracts, at first quickly and then more and more slowly, until a condition of equilibrium is reached. Such, at least, is the case theoretically, but in actual practice it is, as a rule, impossible to keep the tissue in the same condition as regards moisture, absence of putrefactive changes, &c., &c., long enough for us to be able to follow the variations in length of any particular specimen until a state of absolute equilibrium is reached.

In making observations, therefore, on the longitudinal elasticity of animal tissues, we must keep constantly in mind that at no time, in the course of any given experiment, is the specimen with which we are working in a condition of theoretically complete equilibrium with the external forces which are acting upon it. It is always either slowly expanding or slowly contracting.

We cannot explain this after-action, which is so marked a feature of the elastic properties of animal tissues, by ascribing it to imperfect elasticity. The specimen in whose case it presents itself need not have received a permanent set. Within certain limits the return of the tissue to its previous length on removal of the stretching weight seems to be very nearly as complete and exact[1], where due time is allowed, as it is in the case of the most elastic metals. It is only in so far as regards the time-element that animal substances are markedly different from metals in this particular.

The question naturally arises as to whether the internal resistance, which is the cause of the elasticity after-action, be not identical with that which has been described as viscosity in the case of metals[2]. The term viscosity has been applied to a characteristic of the elastic properties of metals, glass, india-rubber, &c., of which, as with the after-action, the time-element is one of the principal factors. Thomson found "by vibrating a spring alternately in air of ordinary pressure and in the exhausted receiver of an air-pump, that there is an internal resistance to its motions immensely greater than the resistance of the air. The same conclusion is to be drawn from the observation made by Kupfer in his great work on the elasticity of metals, that his vibrating springs subsided much more rapidly in their vibrations than rigid pendulums supported on knife-edges. The subsidence of vibrations is probably more rapid in glass than in some of the most elastic metals, as copper, iron, silver, aluminium ; but it is much more rapid than in glass, marvellously rapid indeed, in some metals (as for instance, zinc), and in india-rubber, and even in homogeneous jellies."

That there is some relation between the viscosity described by Thomson and the condition which causes the after-action is apparent when we remember that both in glass and in india-rubber, in which the subsidence of vibrations

[1] The time-curve appears to terminate asymptotically.

[2] Sir W. Thomson. "On the elasticity and viscosity of metals." *Proc. Roy. Soc.*, May, 1865 ; and *Encyclop. Brit.* 9th Ed. Art. Elasticity.

takes place so rapidly, the elasticity after-action is much more strongly marked than in the case with steel, copper, silver, and other highly elastic metals. With regard to the aortic wall, I have found (pursuing indeed a very rough method) that vibrations subside even more rapidly than is the case with strips of india-rubber tested in a similar manner.

It would appear, however, that enough is not yet known concerning the law of molecular friction, whose existence was demonstrated by Thomson's experiments, to allow of any definite conclusion being drawn as to how far the same law will explain the phenomenon of elasticity after-action. This much appears certain, *viz.*, that this molecular resistance in elastic solids, which causes the viscosity of metals, is not simply proportional to the velocity of change of shape. Were this the case, we would be forced to assume that Thomson's viscosity and the molecular friction which causes the elasticity after-action are essentially different in nature.

Of all the animal tissues, the wall of the arteries presents the elasticity after-action in the most marked degree. The extent to which it is present varies considerably with different specimens. In any given artery it is found usually to be least marked immediately after death. We have, unfortunately, no means of learning with accuracy to what extent it is present in the living arterial wall.

In experiments on the longitudinal elasticity of the arterial and venous wall, it is especially necessary to eliminate as completely as possible the influence of the elasticity after-action. This can be done in part by allowing a considerable interval of time to elapse between the application of a weight and the measurement of the elongation which results. Since the time-curve of any given elongation descends with gradually diminishing speed, and afterwards runs asymptotically towards the abscissa, the longer the interval between the application of the weight and the measurement the more accurate will the latter be. Were it possible, we ought to wait in each case until the tissue experimented upon has arrived at complete equilibrium. We cannot, however, with animal tissues, follow the rigorous methods which can be employed by physicists in experimenting on metals. The only course open to us is to be as exact as the nature of the tissue we are engaged upon will admit.

Where we only desire to compare the elasticity curve of one specimen with that of another, we obtain results which are, in all probability, sufficiently accurate, if we allow an interval of 5—10 minutes to elapse between each successive weighting and the measurement which follows it. It is scarcely necessary to add that the intervals between the weightings and the succeeding measurements ought to be of the same length for any series of experiments in which we desire to compare the curves obtained one with another.

One other technical point must be referred to before leaving this part of my subject. As was pointed out by Wundt[1], if, while a portion of tissue is in a state of slow contraction, a weight be applied to expand it, the stretching which results will be less than would have been the case had the tissue been in equilibrium, and *a fortiori* had it been slowly expanding.

If, in measuring, with the view of constructing an elasticity curve, the expansion of a given strip of tissue, produced by gradually increased weightings, we remove one weight before another is applied, each successive weight is added to the tissue while it is in a condition of gradual contraction. A

[1] *Die Lehre von der Muskelbewegung.*

cause of error is thereby introduced which will increase with the increasing weights. This can be avoided if the successive weights are added to those which have already been applied, so that the specimen during the whole of the observation continues expanding.

II. Elasticity of the Arterial Wall.

a. *The relation between the internal pressure and the cubic capacity of the arteries.*

The method which I first employed for investigating this point was the following :—

A portion of artery, so arranged that it could be distended by any desired internal pressure, was inclosed in a small vessel, containing olive oil, and the variations of whose contents were recorded by means of a lever, writing on the blackened surface of a cylinder.

The illustration, Fig. 1, Pl. V., shows the construction of the oil vessel. Its upper opening is closed by a perforated stopper, *d*, through which passes the cannula, *c*. Cannulæ of different diameter were employed for large and small arteries. On the end of the cannula the portion of artery *a*, to be examined, is tied, the other end of the short arterial tube being closed by introducing into it a small wooden plug, *b*, which is grooved to allow of its being tied in with a ligature.

The cannula, *c*, is connected by means of a T tube, on the one hand with a mercury manometer, and on the other with an arrangement by which the pressure of the air within the piece of artery can be raised. This latter consists of a strong caoutchouc bag, compressed by means of a screw between two metal plates. An illustration of it was given in connection with a former paper[1] in the last volume of the Journal.

To return to the oil vessel which contains the piece of artery. At the bottom of this vessel are two openings, one of which is the entrance to a tube, provided with a tap, to allow of the exit or entrance of oil. The larger opening is for the recording arrangement. This latter, as in an instrument which I have already described elsewhere, as used for studying the movements of the frog's heart[2], consists of a light piston, *h*, through the centre of which passes a fine steel needle, *f*. The two guides, *i* i^1,

[1] Roy and Graham Brown. "Blood pressure in the capillaries, &c." This Journal, Vol. II., p. 323.

[2] Roy. This Journal, Vol. I., p. 452.

serve to prevent lateral movement of the piston. As seen in the drawing, the vertical movements are magnified by means of the recording lever.

The oil is prevented from escaping by the side of the piston by means of the fine flexible membrane, *k*. The arrangement of this part of the instrument has been so fully considered in my paper on the frog's heart that I need not refer to it at length here.

With this instrument, then, the addition or the removal of a given portion of the contents of the oil vessel causes a proportionate fall or rise of the lever-point. The relation between the movements of the piston and of the lever-point is more exact than may appear at first sight. As was pointed out by Schmulewitsch[1], when slight movements are magnified by means of a lever the error introduced is excessively slight, so slight that it may safely be ignored in observations like the present.

The pressure of the oil within the vessel is never the same as that of the atmosphere, and this has always been allowed for in my experiments. When in the following pages the intra-arterial pressure is referred to, it must be understood that the zero of the scale is at a point where the internal pressure is the same as that outside the artery.

As the object kept in view was the examination of the elastic properties of the arteries from a physiological and pathological standpoint, the pressures, used to distend the portions of artery taken, were never pushed far beyond the maximum pressures which may occur in them in the living body. For rabbits' vessels 200 mm. of mercury was the upper limit, while with larger animals, such as the dog and cow, the pressures were often raised to 300 mm. Hg.

The first point investigated was the degree to which a portion of aorta or artery expands with each successive increase in the internal pressure, the latter being raised step by step to a height somewhere above the maximum blood pressure of the animal from which the specimen was taken.

In Figs. 4 and 5 of Pl. VI. can be seen the results of two such experiments. They were obtained in the following manner :—A horizontal line having been drawn on the blackened surface of the drum, the point of the recording lever is brought up exactly level with it, a matter which is managed by increasing or diminishing the quantity of oil in the vessel. The pressure within the piece of artery, which has at first been kept below zero (so that the arterial tube is collapsed), is now raised a little above zero—for example, to 1 or 1·5 mm. Hg. The opening out of

[1] Schmulewitsch. *Vierteljahrsch. d. Naturf. Ges. in Zurich*, 1866.

the collapsed artery causes an increase in the contents of the oil vessel, and the lever-point falls to a corresponding extent.

The drum is now rotated, so that the lever-point marks a short horizontal line on its surface. A quantity of oil, sufficient to bring the lever-point back to its original level, is then allowed to escape by opening the tap. The intra-arterial pressure is next raised to 10 mm. of mercury. (It may be remarked parenthetically that, to insure accuracy, a cathetometer was used to read off the height of the mercury column.) After the intra-arterial pressure has been raised, a period of ten minutes is allowed to elapse, the drum being then rotated for a short distance, and the lever-point again brought back to its initial point by opening the tap. The intra-arterial pressure is then at once raised to 20 mm. Hg., and the same process repeated; and so on until a height of 150 or 200 mm. of pressure is reached.

Figs. 4 and 5 from the *aorta thoracica descendens* and the *aorta abdominalis* of two different rabbits were obtained in the above-described manner. Both are from perfectly fresh specimens. I shall have occasion further on to refer to the relation which exists between the cubic capacity of the undistended artery (*i.e.*, with an internal pressure just above zero) and its capacity with higher pressures, and will not therefore refer further to the subject here.

The point of principal interest in connection with tracings such as those copied in Figs. 4 and 5 consists in the fact that the increments of capacity vary in a manner which could scarcely have been anticipated in proportion to the increments of intra-arterial pressure.

The former increase in proportion to the latter until a certain pressure is reached, after which they diminish. The pressure at which an increase by 10 mm. of internal pressure produced the greatest increase in capacity is in Fig. 4, 60 to 70 mm., while in Fig. 5 the maximum increase in contents is from 70 to 80 mm. Hg.

In these two instances, therefore, the portions of aortic tube taken were most distensible, or most elastic, with pressures of about 70 mm. of mercury; or, to put the matter conversely, at these pressures a unit increase in their contents would have produced the smallest change in the intra-arterial pressure. Functionally, the aortic elasticity would, in these two cases, have come most fully into play with pressures of about 70 mm. of mercury. It must be remembered that these are the kind of curves which are always obtained from the aorta of healthy rabbits. The maximum of distensibility is usually found somewhere between 65 and 95 mm. Hg.

And this is a point of considerable interest when we remember that these values correspond to those of the medium blood pressure in the case of rabbits. In them, therefore, the aortic walls are most elastic at pressures corresponding, more or less exactly, to their normal blood pressure.

As will be noticed further on, the same relation exists in the case of the other animals whose arteries were examined.

In Fig. 6, I give a tracing taken in the above-described manner from a portion of the *vena cava inferior* of a cat.

The tracing from the vein shows, as can readily be seen, a very different relation between the internal pressure and the cubic capacity. With veins the maximum of distensibility occurs with pressures immediately above zero. To this point I shall, however, have occasion to return.

After I had taken a considerable number of tracings from different arteries in the above-described manner I was led, from various considerations, to change my method somewhat. That first used is not very convenient for extended observations, and did not appear to me of sufficient accuracy unless much care and attention are expended while taking the tracings.

It was evidently desirable to make use of a method which should be absolutely automatic—in which a clockwork should regulate the variations in pressure and the recording of the changes in capacity of the artery.

The method which I eventually found best fitted to fulfil these conditions is illustrated by the diagram Fig. 2, Pl. V.

The drum, *a*, of the clockwork is blackened only on its upper three-fourths, the lower fourth being left uncovered with paper; and round this part of it passes the strong endless silk thread, *b*.

This thread communicates the motion of the revolving drum to one of the pulleys, *c*. These two pulleys are of the same diameter, and are fixed on the same horizontal axle, so that they move together. Round the second of these two another silk thread makes one turn. At the one end of this thread is a scale for weights, *g*, used to counterbalance a mercury reservoir, *h*, which is suspended from its other end, the thread being passed over a larger pulley, *f*.

Connecting the wide open mercury reservoir, *h*, with the small pressure vessel, *i*, is a flexible tube. Another tube, *k*, of narrow calibre brings the interior of this vessel, *i*, in communication with the cannula upon which the bit of artery is tied. The reservoir, *h*, and the tube hich joins it with the vessel, *i*, are filled with mercury, which also half fills the vessel, *i*. The upper half of this vessel, the tube, *k*, and the portion of artery contain air. The piece of artery is inclosed in oil in the same kind of vessel as that described above.

With this arrangement the difference in level of the mercury in the reservoir, *h*, and the pressure vessel, *i*, corresponds with the pressure within the piece of artery. By the arrangement of the silk cords the reservoir is raised or lowered in proportion to the movement of the drum of the clockwork.

Since the two pulleys, *c*, are of equal diameter, the rate of movement, up or down, of the mercury reservoir, is exactly the same as the rate at which the blackened surface of the drum moves past a fixed point.

For example, one inch of an abscissa, drawn horizontally on the drum's surface, corresponds to a rise or descent of the mercury reservoir of exactly one inch.

In taking tracings with this arrangement the mercury reservoir is either slowly raised or slowly lowered, and, in the curves obtained, the pressures in the portion of artery are the abscissæ; and, since the vertical movements of the point of the recording lever are proportionate to the variations in the capacity of the portion of artery, the ordinates of the curve obtained are the cubic capacities of specimen of artery examined.

By the use of very wide vessels for the mercury reservoir and the pressure vessel, *i*, we avoid, more or less completely, the error which would otherwise be introduced owing to compression of the air contained in the upper part of the vessel, *i*, and in the narrow tube going from it to the cannula, as well as from the variations in capacity of the portion of artery examined. By the use of wide shallow vessels, and by taking care that as little air as possible is contained in the upper part of the compression vessel, the error due to the want of exact correspondence between the movements of the reservoir and the difference in height of the two mercury surfaces may be so greatly reduced that its influence may, in practice, be safely ignored. At first, indeed, I made corrections of my curves with the view of eliminating this error, but I soon found it to be excessively slight, and not of a kind which could possibly modify to any noteworthy extent the character of the tracings obtained.

In working with this method the rate of movement of the drum was usually very slow, so that 20 minutes, or half an hour in some cases, was passed in raising or lowering the intra-arterial pressure gradually from zero to 200 mm. of mercury, or *vice versâ*. This was done with the view of reducing to a minimum any disturbing influence due to the after-action. Comparative experiments showed, however, that the curves taken very slowly are the same in form as those taken rapidly, *e.g.*, in two or three minutes.

Figures 8, 9 and 11, Pl. VI., are examples of curves taken from the arteries of healthy animals in this manner.

Fig. 8 is from a portion of the *aorta thoracica* of the rabbit, while Fig. 9 is from the carotid of the same animal, both curves having been taken immediately after the animal had been killed. Fig. 11 is from a portion of the *aorta thoracica descendens* of a cat.

These three tracings may be taken as showing the usual form of curves obtained from the arteries of perfectly healthy animals. They exhibit a marked general resemblance.

On the intra-arterial pressure rising above the extra-arterial the lever-point falls, and the extent of this fall gives us the cubic capacity of the portion of artery in its undistended condition. As the pressure within the artery is gradually increased the lever-point descends, at first slowly and then more rapidly, with still higher pressures, however, diminishing more and more in rapidity of fall. In the case of Figs. 8 and 9, from the aorta and carotid of the rabbit, the point at which the fall of the lever-point is greatest for a given rise of the intra-arterial pressure is somewhere about 70 mm. from the point where the collapsed artery opened out. These two vessels were, therefore, most distensible with a pressure of about 70 mm. of mercury. In the case of the cat's aorta (Fig. 11) the greatest variation in contents with unit rise of pressure is reached with a somewhat higher pressure than with the rabbit's aorta.

These curves, then, show the same peculiarity as the tracings taken by the less accurate method first employed.

Before proceeding to compare the elasticity curves of different arteries, I must say a word, first, as to the effect of *post-mortem* changes on the elasticity of the blood vessels, and secondly, as to the effect produced on the curve, according as the intra-arterial pressure is slowly increased from below zero to a given height, or slowly diminished from, let us say, 200 mm. Hg. to below 0°.

Until putrefaction is far advanced the elasticity curve of any given artery remains the same. Even when putrefaction is in active progress the form of the curve is the same as that from a perfectly fresh specimen.

The chief difference appears to lie in the fact that the after-action becomes more and more pronounced after the setting in of putrefactive changes. From the time of death to that when putrefaction has commenced the elasticity of the arteries remains the same. In experimenting on the elasticity of human arteries, therefore, no error is introduced owing to the interval which has necessarily elapsed between death and the *post-mortem* examination.

When the curves are not taken too fast, they are the same as to form for any given specimen of artery, whether they have been taken by increasing the pressures used or gradually diminishing them.

b. *Relation of capacity to internal pressure in different arteries of the same animal.*

Considered from a functional point of view, it may be said that the elastic properties of the aorta and large arteries of any given animal are identical. Curves taken from different parts of the same aorta present an exceedingly striking resemblance. The relation of the capacity when undistended to that when the vessel is distended by any given pressure is the same for all parts of the aorta. The point, therefore, where unit rise of pressure causes the maximum increase in capacity is the same at every part of the vessel.

The same similarity is found when we compare the curves from the femoral and carotid arteries with those from the aorta of the same animal.

This is pretty well seen in the two Figs. 8 and 9 from the carotid and the aorta respectively, of the same rabbit. As the curves show, the point of maximum distensibility is reached with the same pressure in both. In the case of dogs and cats, and also in the human arteries, the elasticity curves, taken in the above-described manner, from different vessels of any particular animal or man, resemble one another in their characters so closely that the possibility of the resemblance being accidental cannot for a moment be entertained. The elastic properties of arteries from different animals of the same species may vary considerably, as I shall have occasion to point out, and still greater differences are the result of malnutrition, such as that produced by febrile processes; but only in cases where unequally distributed structural change is present do the elastic properties (considered from a functional point of view) of the different parts of the arterial tree differ from one another.

One difference does, however, exist, but it is of the nature of those exceptions which go to prove the rule. In the aorta and its principal branches the ratio of capacity to pressure is the same, but the aorta is relatively wider in the undistended condition than the vessels which leave it. This is shown by the fact that the relation of the capacity in the undistended condition, to that when distended by a given internal pressure, *e.g.*, 200 mm. Hg., is not the same in all the arteries of an animal. If the reader will compare the curves, Figs. 8 and 9, he will see this. On comparing the extent of the abrupt fall of the lever-point (corresponding with the change of internal pressure from negative to positive) with the fall which it is seen to present with 200 mm. Hg. pressure, he will find on measurement that taking the capacity in the undistended condition (equal to the extent of the primary fall of the lever) as 100 in each case, in Fig. 9 the capacity at 200 mm. Hg. is equal to 400, while in Fig. 8 the capacity at the same pressure is equal to 640 or thereabouts. Roughly speaking, the capacity of the aorta has become quadrupled by raising the intra-arterial pressure to 200 mm., while that of the carotid of the same animal is more than six times as great at that pressure as it was in the undistended condition.

In all animals examined this difference in arteries of different calibre was found to exist. It shows us that the mechanism by which identical functional elastic properties are conferred on the different parts of the arterial tree is not the same for arteries of different diameter.

That I may not require to return to the subject, I will refer here to the differences on this point which exist in different animals.

For the *aorta of the rabbit*, the relation between the capacity when undistended and the capacity with an internal pressure of 200 mm. Hg. is very nearly the same in different individuals. As in the specimen from which Fig. 9 was obtained, the ratio is, in healthy animals, about 1 to 4. On measuring out some thirty curves which I have taken from rabbits' aortas, I find that the departures from this relation are slight, and only occur in one or two instances ; and, in these, the animals from which the specimens were taken may not have been perfectly healthy.

In one case, instead of being as 1 is to 4, the ratio of capacity when unstretched to that at 200 mm. pressure is as 1 is to 3·6 ; in another it is as 1 is to 4·3. These two are the ones which depart most from the usual relation of the two capacities.

With the *carotids* and *femorals of the rabbit* the relation of the two capacities varies more in different individuals than is the case with the aorta. A relation of 1 to 6 is that most commonly met with. In one case I find a ratio of 1 to 5·3, and in another of 1 to 7·6. All my other curves from these vessels of the rabbit show relations somewhere between these.

For the *aorta of the cat*, of which I possess fewer curves than from the same vessel of the rabbit, the capacities at 0° and 200 mm. respectively, stand, in nearly all, in the relation of 1 to 5·5. In one case the relation was that of 1 to 6.

For the *carotids and femorals* of the cat, the relation was that of 1 to 6 or 1 to 7.

In the case of the *dog's aorta* the relation was usually 1 to about 5, while, with the *carotids* of the same animal, the ratio of the two capacities was 1 to 6·5 or 1 to 7.

The *veins* distinguish themselves from the arteries by the relatively small increase in capacity produced by raising the internal pressure from immediately above zero to a height when their curve of contents begins to run asymptotically. The ratio, in the veins examined, of the capacity at zero to that, *e.g.*, at 400 or 500 mm. of water, was usually about 1 to 2.

The enormous changes in the capacity of the veins during life are, therefore, evidently due less to differences in the pressure than to the great differences in the quantity of blood which they contain.

On the other hand, the pulmonary artery distinguishes itself by its excessive elastic distensibility. In the case of more than one specimen of rabbit's pulmonary artery the capacity became, on raising the internal pressure up to 500 mm. of water, more than twelve times as great as that when undistended.

c. *Elasticity curves of arteries from different species of animals.*

All the capacity curves of arteries from healthy animals which I possess resemble in form those seen in Figs. 8, 9, and 10, whatever the species. In all cases the curve is at its first part convex on the side next the axis (above in the curves), afterwards becoming concave. In the case of rabbits, what I have already said, together with the curves, Figs. 8 and 9, sufficiently indicate what are the characteristics of the normal curve. In them the pressure at which the artery, considered in relation to its capacity, is most distensible is usually about 70 mm. Hg.

In the case of cats this point is reached with a somewhat higher pressure ; varying a good deal in different animals, it is usually at about 110 or 120.

With dogs this point is usually a little higher than with cats. The height of the pressure at which it occurs varies more with different individuals than is the case with rabbits' arteries.

This form of curve is, as already stated, different from that of veins. In them, whether large or small vessels are taken, the curves obtained resemble a hyperbola—the distensibility is greatest immediately above zero internal pressure. In taking curves from veins I did not employ mercurial, but water pressure in the reservoir and pressure vessel of the arrangement above-described, as being more nearly related to the pressures which the blood may present in them in the living animal.

The form of curve given by the pulmonary artery resembles that of the systemic arteries. For it, also, water replaced the mercury pressure used for the aorta and its branches. The pressure at which the curve ceases to be convex to become concave towards the axis is, in the curves which I possess from the pulmonary artery of rabbits, from 200 to 250 mm. of water.

In the case of the pulmonary artery of the cat, the maximum change of capacity with unit change of pressure was found in one case to be at 300, and in another at 380 mm. water.

d. *Effect of disease on the elasticity of the arteries.*

As yet the elastic properties of normal vessels have alone been considered. It was evident, however, at an early stage of my investigations, that disease exercises a very important influence on the elasticity of the arteries, and that in cases where no macro- or microscopic change of structure could be found.

This was first made evident to me by the case of a dog which was brought to the Strassburg laboratory in a state of extreme emaciation, either from starvation or some chronic illness. As it did not gain flesh, although plenty of nourishment was provided, it was condemned to be killed, as useless for physiological purposes ; and it is from one of the carotids of this animal that the tracing Fig. 10 was obtained, the arrangement employed being in every respect the same as that used when tracings 8, 9, and 11 were taken.

The first point that strikes the eye in this curve is the fact that the maximum of expansion with a given increase of the internal pressure is no longer at about 120 to 160 mm. Hg., as is the case with healthy animals, but is immediately above zero pressure. The artery was the more distensible the lower the intra-vascular pressure. This tracing presents another peculiarity which of itself would suffice to distinguish it from those obtained from the arteries of healthy animals. The capacity just above zero pressure is much greater compared with that at a given high pressure, *e.g.*, 200, than is normally the case. The ratio of the two capacities, instead of being, as is normally the case, as 1 is to 6·5 or 1 to 7, is here as 1 is to 2·6—a difference which is sufficiently striking. And it was not in the case of its carotids alone that the elasticity curves of this animal's arteries differed from those of healthy animals. A change of the same kind, and to a corresponding extent, shows itself in curves taken from the femorals and from the aorta. In the femorals the ratio of capacity at zero to that at 200 mm. Hg. was found to be much the same as in the carotids, being as 1 is to 2·8. In the aorta the ratio is 1 to 2. The form of the curve was found to be exactly the same in the different vessels examined.

The illness, or long-continued ill-treatment, of this poor beast had thus resulted in a strikingly marked change in the elasticity of its arteries—a change so great that the curves obtained from them may almost be said to have nothing in common with those which represent the elasticity of the normal, healthy arterial tube. Yet in this case no structural change of the walls of the vessel could be detected either by the naked eye or by careful microscopical investigation of hardened specimens.

The question naturally arises—in what way had the elastic attributes of the vessels become so modified? Had the arteries become wider in their undistended condition? or had they remained of normal diameter, but become more rigid, this increased rigidity being accompanied by some change in the statical relations of the ultimate molecules of the elastic elements, such as would explain the change in the form of the curve?

At the time when the case came under my notice I had no means of deciding which of these two explanations was the correct one.

I had soon, however, opportunity of comparing the elastic properties of this animal's arteries with those of other dogs in which the same peculiarities were present, though to a less marked degree. During the time that I acted as assistant at the Strassburg Physiological Institute several cases occurred of dogs which, after oft-repeated operations on the brain, were at last seized with a form of cerebral meningitis, ending fatally after having caused more or less marked fever marasmus. Curves which were obtained from the arteries of these animals present all shades of variety between the typical curve of healthy arteries and the one represented in Fig. 10. These curves show that, with increasing marasmus, the point of maximum distensibility with unit variation of internal pressure is reached with lower and lower pressures. The arteries are relatively most elastic with lower pressures than in the case of healthy vessels, and the more advanced the marasmus the lower is the pressure which corresponds to the maximum distensibility of the animal's arteries. Hand-in-hand with this change proceeds that of the ratio of capacity when undistended to that when distended by tolerably high pressures, such as 200 mm. Hg.

This pathological change in the elasticity of the arteries is, therefore, due to these vessels remaining abnormally wide (at zero pressure). Their walls have received a permanent set, and only a part of the curve given by normal arteries remains.

The curve of Fig. 10 corresponds to that part of the curves given in Figs. 8, 9 and 11, which is obtained with pressures higher than the medium blood pressures of the animals from which they were taken—to that part of these curves which is concave towards the axis. This change in the elasticity of these arteries is, to all appearance, principally, if not entirely, due to the elasticity having become less perfect during life. It is very curious, from a teleological point of view, to find that this pathological change renders the vessels relatively most elastic with subnormal blood pressures, such as exist in the living animal in conditions of fever and marasmus like those affecting the animals in question.

On extending my observations to the elasticity of the blood vessels of man I soon found that this pathological change in the elastic properties of the arteries is of extremely common occurrence.

In all cases examined, in which the person's death was preceded by lingering illness, accompanied by marasmus, it was found to be present; while, on the other hand, curves from well nourished children —those, for example, dying of some rapidly fatal disease—were found to be identical in form with those which I have above described as the normal curve of healthy arteries.

I possess several curves, taken from young persons who had succumbed to some lingering illness, causing emaciation and marasmus, which resemble so closely, in every particular, that given in Fig. 10 that one would, at first sight, imagine they must have been obtained from the same case.

I have, as yet, said little or nothing concerning the normal elasticity of the arteries of man, the reason being that it is impossible to deal with this subject satisfactorily without at the same time taking into consideration the effect both of age and of disease. The observations which I made on human arteries with the method above-described soon convinced me that much of interest might be learned from a series of investigations on the modifications in the elasticity of the arteries which are produced by various diseases, and also, that only from a prolonged series of inquiries would it be possible to obtain trustworthy data either as to the effect of disease or of age on the arterial walls. In the case of man we cannot, of course, modify the conditions as to health, age, &c., to anything like the extent which is possible with animals. In investigating the influence of age we cannot exclude the influence of disease (except in cases of death from accident, and such cases are not always available). Nor, on the other hand, can the influence produced by various diseases on the elasticity of the arteries be studied satisfactorily until the effect of age has first been learned.

III. Longitudinal Elasticity of the Arterial Wall.

a. *Normal elasticity curve.*

On deciding to undertake a series of investigations on the elasticity of human arteries, sufficiently extended to allow of definite conclusions being drawn as to the effect of age and some of the commoner types of disease, I found it necessary to change my method of inquiry.

In Professor v. Recklinghausen's Institute, where I made the most of these observations, it is the usual custom to slit open the aorta and its larger branches during the *post-mortem* examination.

Had I kept to the above-described method, therefore, which requires that the arteries examined should not be cut open, my supply of material would have been very limited, and I would have been unable to examine the elasticity of those specimens which I most wished to investigate, viz., those in which structural disease, such as aneurism or atheroma, was present. Moreover, the mechanism by which a curve of contents with varying pressures, so peculiar, and so well suited to the functional requirements of the circulatory system as that above-described, was produced did not seem by any means clear. I was in hopes that a study of the longitudinal elasticity of strips of aortic and arterial wall, taken both longitudinally and transversely to the axis of the vessel, would throw some light on this subject.

At first I employed the time-honoured method usually employed for such investigations, viz., hanging up strips of arterial or aortic wall of a given breadth, and stretching them by means of weights, the strains produced being read off by means of a cathetometer. This method I soon found excessively wearisome and by no means so accurate as it appears at first sight, unless a considerable number of precautions are taken. What especially unfitted it for my purpose was the fact that the expenditure of a good deal of time is unavoidable with it, and this involves a corresponding diminution of the number of specimens which can be examined.

I therefore sought to find some automatic method, and finally got the instrument seen in Fig. 3, Pl. V., constructed.

It leaves little to be desired either in the way of convenience or accuracy[1].

It is so constructed that (by means of a clockwork if desired) the weights applied may be gradually increased, while the elongations thereby produced are recorded by a lever writing on paper, which is moved horizontally past the lever-point with a rapidity which exactly corresponds to the rate at which the weights applied to the portion of tissue are augmented. In the curves obtained, therefore, the abscissæ are the weights employed, and the ordinates the elongations of the strip of tissue.

The strong metal pillar, *k*, with the movable arm, serves to support firmly the upper end of the strip of tissue, which is held by the screw clamp, *g*, and which is suspended directly above the long horizontal lever, *e*, *a*. The clamp, *g*, at the lower end of the strip is connected by a hook with the lever, in which holes have been bored at regular intervals to receive it.

On the lever is a sliding runner, *d*, which supports a scale for weights, and which can be slid, with exceedingly little friction, from the fulcrum towards the point of the lever.

The runner, *d*, and the hook, *g*, are of such a form that the former can be moved past the latter without coming in contact with it. When the runner, and the scale which is attached to it, are moved away from the fulcrum of the lever the weight which acts on the strip of tissue is, of course, correspondingly increased.

The outer half of the lever (which is not reached by the runner) is thinner and lighter than the inner half, and has, at its extremity, a fine glass pen for writing on the piece of paper which is clamped on the

[1] Its principle is the same as that of Blix[2], although I believe it presents certain advantages over that employed by him. When I got the instrument made I was aware of the principle of the method used by Blix, and which was suggested to him by Holmgren, but I could not learn anything concerning the details of his apparatus, so that the one illustrated by Fig. 3 bears little external resemblance to the one used by the Swedish investigator.

[2] Blix, "Bidrag till läran om muskelelasticiteten." *Upsala Läkareförenings Förhandlingar*, IX., p. 555, 1874.

surface of the brass plate, *a*. This plate can be moved horizontally along the two wire guides, *b b*. At its right-hand end is a peg from which a silk thread passes to the runner, *d*. Thus, when the plate is drawn along the guides towards the right-hand side of the instrument, the weights are drawn at the same rate away from the fulcrum of the lever. Finally, the counter weight, *f*, enables us to counterbalance the weight of the lever and any weights in the scale before a curve is taken, so that, at the commencement of the curve, the tissue is only stretched by the weight of the light clamp at its lower end.

I soon discovered that by drawing the plate *a* very slowly to the right with the hand, the curves obtained are, practically, quite as accurate as when a clockwork is used, so that in the most of my measurements I dispensed with the latter.

The breadth of the strip chosen was always 1 centimeter, its length varying with its longitudinal elasticity.

As a rule two curves were taken on the same sheet of paper, one from a strip taken in the direction of the length of the aorta or artery, and another, of exactly the same length and breadth, taken in the transverse direction. The curves of longitudinal elasticity in the transverse and longitudinal direction of the wall of the vessel could thus be compared at a glance.

Any drying of the specimens during the measurement of their elasticity was prevented, it should be added, by frequent pencilling with ·75 per cent. salt solution. In cases of arterial disease the specimens were examined microscopically in order to arrive at some knowledge of the change of structure which caused any given deviation from the normal elasticity curve.

In the present communication, however, I will only refer to the elasticity of healthy arteries, and to the modifications which result from the effect of age. Pathological changes I will deal with in a separate paper.

The curves which are reproduced on Pl. VII. are examples of tracings taken, with the instrument just described, from the aorta of human subjects of various ages.

In all of these curves the figures marked on the right-hand side—the ordinates—are the lengths of the strips taken, the upper number in each case being the length of the strip when unstretched.

The figures marked beneath the curves—the abscissæ—are the weights employed, which in each case, as can be seen, were raised from 0 up to 200 grammes.

The values of the abscissæ are, therefore, the same in all of these curves. The vertical lines, placed 1 centimeter apart, are curved, and their curvature is that of a circle whose radius has the same length as the lever employed. They give, therefore, the correction necessitated by the fact that the lever-point does not describe a straight vertical line.

The horizontal lines are 5 mm. apart, and, since the variations in length of the strips examined were magnified five times by means of the lever, the intervals between these lines are equivalent to 1 mm. of the length of the strip.

In all of the curves on Pl. VII. the elongations of the strips were magnified five times by the lever. The initial length of the strips taken was not the same for the different figures, but varied according as the aorta examined was found to be more or less elastic.

Fig. 12 is from the *aorta thoracica descendens* of a female child, æt. 2½ years. Death caused by *diphtheritis*, complicated by *broncho-pneumonia.* No emaciation. Circumference of aorta beyond arch = 23 mm.

Fig. 13 is from a female, æt. 22. Death due to septic poisoning after child-bed. Curves are from *aorta thoracica descendens,* the circumference of the vessel at that part being 45 mm.

Fig. 14 is from a male, æt. 26, who succumbed to a rapidly fatal pneumonia. Circumference of aorta at part taken, viz., middle of thoracic portion, was 50 mm.

In none of these three cases was there any appearance of disease affecting the aorta. They resemble, moreover, very closely the curves which are obtained with the same instrument from the aorta of the dog, cat, or sheep. They are, then, the curves given by healthy aortas.

In all of them it can be seen that the longitudinal strip expands with light weights more readily than the transverse strip, but that with heavier weights this relation is reversed, and the curves cut one another. For example, in Fig. 12, with weights below 90 grammes, the longitudinal strip was longer than the transverse, while with weights above 90 grammes the reverse was the case.

The curves of longitudinal elasticity of strips of aorta taken transversely and longitudinally do not always cut one another. Exceptions occur even with perfectly healthy vessels. Of this an example can be seen in Fig. 17, which is from the aorta of a female child, aged 9 years. *Broncho-pneumonia* was the cause of death, the aorta being to all appearance perfectly healthy. In this tracing the upper of the four curves is from a transverse strip, and the third (counting from above) from a longitudinal. In this case, it can be seen, that with light weights, the longitudinal is more expansible than the transverse, and that this relation becomes reversed with higher weights. Curiously enough, in this particular instance, the longitudinal strip was again more expansible than the transverse when weights varying from 140 to 200 grammes were employed. The curves in this case do not cross, but in their general relation to one another there is an undeniable similarity to the curves given in Figs. 12, 13, and 14.

Before coming to speak of the influence of age in modifying the elasticity curves of the arteries it may be as well to say a word as to the relation between curves taken with this instrument and the curves of capacity which were above described.

I do not intend in the present communication to refer to the mathematical formula by which the pressure and volume curves can be converted into the curves of longitudinal elasticity of the arterial wall or *vice versâ.* To insure accuracy in a subject of this kind, where it is a question of exceedingly small amounts, it would be necessary in verifying the formula by direct experiment to control the pressure and volume curves in one particular. In my observations on the relation between the internal pressures and the capacity no account was taken of any slight want of parallelism in the walls of the portions of artery taken, and although this will not interfere with the general conclusions which I have drawn from the form of the curves in different instances, it suffices to prevent our applying to them, without correction, mathematical formulæ which are only strictly applicable to the true cylinder.

My attention has been called to this point by my friend Prof. Dewar, and in a future communication I propose to return to the subject, after having made experiments suited to control more completely the form of the pressure and volume curves.

But although strict mathematical treatment is scarcely applicable, it is not difficult to see in what points the pressure and volume curves are related to the curves of longitudinal elasticity which are represented on Pl. VII.[1]

We know that in the case of a cylinder whose elastic walls follow

[1] The relation in the lengths of transverse and longitudinal strips of aortic wall stretched by like weights cannot, as need perhaps scarcely be said, be held to correspond to the relation in length of transverse and longitudinal elements of the wall when a portion of the aorta is distended by gradually increasing internal pressures. In the case of a cylinder whose walls are composed of an isotropic, incompressible elastic solid whose elasticity follows Hooke's law, the length of the cylinder will not increase at all on its being distended by raising the pressure in its interior. This deduction from mathematical considerations is not completely applicable to the arterial wall which is not composed of an isotropic substance. We may possibly deduce from it, however, that the marked lengthening of the artèries with each pulse-wave in certain cases of disease may be due to

Hooke's law the increments in volume produced by gradual rise in internal pressure increase disproportionately to the pressures used. With such a cylinder, taking the volumes as ordinates and the pressures as abscissæ, the curve obtained is convex towards the axis. It, in fact, resembles the first part of such a curve, for example, as that in Fig. 9—that which was obtained in that instance with pressures varying from 0° up to 70 or 80 mm. of mercury.

A glance at Figs. 12, 13, 14, or, better still perhaps, at Fig. 17, will show that at first the curves from the transverse strips, although not straight in the first part of their course, yet have a very decided tendency towards the straight. These curves are not simple hyperbolas, they are rather of the nature of hyperbolic parabolas. With light weights, for example, from 0 up to 80 grammes, the transverse strip of the specimen from which Fig. 17 was taken has a tendency to follow Hooke's law, *i.e.*, to give a straight line with a curve constructed in this manner.

The longitudinal strips have also a tendency, in the curves of Figs. 12, 13, 14, and 17, to follow a straight course with light weights; but these curves are of infinitely less importance, for reasons which need not be referred to here, than the elasticity curves of transverse portions, in so far as concerns the relation which the elasticity of the walls of the arteries bears to their curves of volume and internal pressure.

The elasticity curves of the transverse strips (which I will alone take into account at present) of the tracings on Pl. VII. are none of them perfectly straight in the first part of their course. Nor, it must be remembered, is it necessary that they should be so in order that the part of a volume and pressure curve to which they correspond should be convex towards the axis. It suffices for this that the curves should not be too far removed from the straight.

The more the elasticity curves of the transverse strips tend to approach a straight line in the first part of their course, the more would the increments in volume, of the portion of artery from which the strips were taken, increase in proportion to the internal pressures. To go into this question more closely, without the aid of mathematics, is scarcely possible. What has been said indicates the results which may be drawn from a rough comparison of curves taken from the same specimen by the two methods which I have employed.

great expansibility of the longitudinal as compared with the transverse elements of the walls of the arteries in these cases. In several instances, usually of old people, I have found the relation between the expansibility of longitudinal and transverse strips to have undergone a considerable change in favour of the former.

b. *Influence of age on the elastic properties of human arteries.*

The tracings, given on Pl. VII., admit of a comparison of the elasticity curves from aortas of persons of early, middle, and advanced ages, all of whom succumbed to rapidly fatal diseases, neither affecting, to a marked degree, the arterial system specially, nor reducing the general nutrition of the body.

Figs. 12 and 17 are from the aortas of two children of the ages of $2\frac{1}{2}$ and 9 years respectively. The form of the curves from the transverse strips is the same in both. They both show an evident tendency towards the straight in the first part of their course.

In the case of the older child (Fig. 17), however, the strip takes its principal bend with weights somewhat higher than in the case of the specimen from the younger child. In Fig. 17, in other words, the curve continues its descending course longer than the curve of Fig. 12. The relation of the length when unstretched to that when stretched by a weight of, *e.g.*, 200 grammes, is very nearly the same in both cases. Taking the length when unexpanded as being, in each case, equal to 100, the length with a weight of 200 grammes is, in the case of Fig. 12, equal to 159, while in Fig. 17 it corresponds to 160.

If we compare these curves with Figs. 13 and 14, from a woman and a man between the ages of 20 and 30, we find that, even with persons below 30, the influence of age has begun to manifest itself. In Figs. 13 and 14 the curves of the transverse strips are further removed from the straight at the first part of their course than is the case with the corresponding curves from the aortas of the children. They are less fitted, therefore, to give the typical, normal volume and pressure curve with a marked convexity towards the axis in the first part of its course. Nor is this accidental in these two instances; even at so low an age as 20 I have never met with curves of the typically normal form which is found in the case of quite young children and healthy animals.

On the other hand, these two curves show that the aortic walls of healthy persons of the age of 20 to 30 are quite as expansible as those of healthy children. And this implies, taking the difference in circumference of the vessels at the two ages into account, and considering the elasticity of their walls in relation to their contents as tubes, that the aortas of full-grown persons are more elastic than those of young children.

To show how nearly the ratio of expansion to the weights employed is tho same in the four specimens from which curves 12, 13, 14, and 17 were taken, I give in a tabular form, and taking the length of the strips when unstretched as 100 in each case, their respective lengths with weights of 50, 100, and 200 grammes:—

Aet.	Curve.	Length Unstretched.	With 50 grammes hung on.	With 100 grammes hung on.	With 200 grammes hung on.
$2\frac{1}{2}$ years	12	100	131	148	159
22 „	13	100	126	143	153
26 „	14	100	128	149	168
9 „	17	100	128	149	160

The ratio of expansion to weights, in the case of the transverse strips from these four specimens, is therefore much the same for all of them.

The curve of Fig. 14 from the man presents a peculiarity which is still more marked in the arteries of muscular, athletic persons. The transverse strip of this specimen, as can be seen from the curve, is more elastic with heavy weights than any of the others. The aorta of this man was more expansible with high pressures than was the case with the woman's orta of Fig. 13, for example.

And a comparison of my curves from the aortas of male and female subjects show that for equal ages the male aorta is almost invariably more expansible, or more elastic, with high weights, such as 200 grammes, than the female aorta.

With a weight of 200 grammes the transverse strip of aorta which gave the curve of Fig. 14 is a little longer, in relation to its length when unstretched, than any of the other specimens from which the other curves were taken. With muscular subjects this characteristic is usually present, and often to a much more marked extent.

When we come to examine the aortas of persons of advanced age we find that a striking change has occurred in the longitudinal elasticity of their walls.

Fig. 15 is from the aorta of a female, æt. 76, whose aorta presented slight traces of atheroma at the point of exit of some of its branches. The part taken was, however, free from atheromatous changes. On the whole the vessel was unusually free from disease for so old a person.

The circumference of the aorta at the part taken (descending thoracic) was 55 mm.

Fig. 16 is from another female, age 71. Death was caused by cerebral hæmorrhage. Scattered irregularly over the interior of the aorta were atheromatous patches, mostly of small size, but the part taken was unaffected. Circumference of the aorta beyond the arch was 52 mm.

The form of the curves in these two cases are different from that of the others on the same plate. Only with light weights up to 50 or 60 grammes are the strips tolerably elastic, and even with light weights they are much less elastic than the others, as the following table of their lengths with various weights will show:—

Aet.	Length Unstretched.	With 50 grammes hung on.	With 100 grammes hung on.	With 200 grammes hung on.
76 years	100	117	122	123
71 „	100	113	117	121

Between curves such as those of Figs. 15 and 16, and those such as Figs. 13 and 14, all varieties are encountered at different ages. At an age of 70 or thereabouts I have never met with aortas which were much more elastic than the two examples I have given. But at ages between 40 and 50, for example, great differences in elasticity are found between vessels of different individuals.

It is needless to insist on the nature of the change in the elasticity of the arteries which occurs in old people. The curves which I have given will, it is believed, make this sufficiently evident. The curve of cubic contents with the internal pressures of arteries whose walls give elasticity curves such as those of Figs. 15 and 16 resemble in form that given in Fig. 10, Pl. VI., from the marantic dog. There are however, many points of difference between the change of the elasticity of the arteries produced, *e.g.*, by wasting fevers, and that which results from the effects of old age. This matter, however, as well as the peculiar changes in the elasticity which accompany some special forms of disease, such as chlorosis, can be more conveniently considered in a future paper.

Before leaving this part of my subject I may refer to the question as to the distribution of the elastic resistance to stretching in the different coats of the aorta.

It is very easy, as need scarcely be remarked, to separate the different layers of the aorta from one another.

In the case of transverse strips from normal aortas removal of the intima makes but little difference in the elasticity curve, as can be seen in Fig. 17, where the upper curve is from the intact strip, and the second from the same transverse strip after the intima had been more or less completely removed.

For transverse strips the elastic resistance to stretching offered by the adventitia is also excessively slight compared with that offered by the media. The curve taken with the media alone is thus practically the same as that obtained from the strip before the intima and adventia have been torn away.

With longitudinal strips the case is different. In them both intima and adventia play important parts in resisting the stretching produced by weights. The difference produced by removal of the intima can be seen in Fig. 17, where the two lower curves are from the longitudinal strip before and after the intima had been removed. As can be seen, this difference is most marked with weights up to 70 to 80 grammes. On the other hand the difference on the expansions, produced by removal of the adventitia is, with longitudinal strips, most marked with heavy weights.

As already remarked, however, the elasticity of longitudinal strips of aortic wall are incomparably less important than that of strips taken transversely to the length of the vessel.

Such are the facts in the case of the aortas of young healthy subjects. In persons of very advanced age, however, the resistance of the different layers of the aorta, as compared with one another, is found to have undergone a change which is of interest, from a pathological point of view, in connection with the subject of the rupture of vessels and the production of aneurism. From the curves reproduced in Fig. 16 it can be seen that, in this case, removal of the intima did not leave the elastic resistance of the transverse strip unchanged. After removal of the inner coat the curve falls more rapidly than before, especially with light weights. In this instance removal of the adventia had but slight influence on the course of the curve; such is not, however, always the case with the aortas of old people. There was no evident structural change in the intima at the part taken in this case, it must be remembered. Where structural change exists, the change in the elastic properties of the aortic wall are much more marked than any that I have referred to in the above pages.

c. *The form of the curve of longitudinal elasticity of the arterial wall.*

As may have been gathered from the foregoing pages, the results which I have obtained in my investigations do not coincide with those of other workers on the elasticity of animal tissues. These have, I believe, without exception found the elasticity curve of the tissues which they examined on this point to be of some definite form which they seem to hold applicable to all specimens.

The most favourite curve is the hyperbola, which was first found by Werthheim[1], for all moist organic tissues. As regards muscles, the experiments of Werthheim have been confirmed by a considerable number of later observers[2]. Others, again, have obtained different results. Wundt[3], for example, found that on using only very light weights the elongations are proportional to the weights employed. v. Wittich[4] also found for muscle that the curve of elasticity is at first more or less straight—that, in fact, within certain narrow limits the elasticity of muscles follows Hooke's law.

In the case of the muscles of the arm of man, Donders and van Mansvelt[5] found the elongations proportional to the weights employed. The method employed by them was, however, by no means of a kind fitted to inspire confidence in the accuracy of the results obtained. Braune[6] found, on stretching veins in the direction of their length, that the elongations at first are sensibly proportionate to the weights used, the curves afterwards becoming hyperbolic. Bardeleben[7], again, found that the elasticity curves of veins are parabolas. An ellipse and a logarithmic line are held by others to express most accurately the elasticity curve of animal tissues.

The only designation which would include the different curves which

[1] *Ann. d. Chimie et Phys.*, xxi., p. 385, 1847.

[2] *e.g.*, E. Weber. Wagner's *Handwörterbuch*, III., 2, 1846. Heidenhain, *Physiologische Studien*, Berlin, 1846. Volkmann, *Arch. f. Anat. u. Physiologie*, 1859, S. 293, &c , &c.

[3] *Die Lehre von der Muskelbewegung*, S. 32.

[4] *Ber. üb. d. Naturf.-Vers. zu Hannover*, 1865, S. 238.

[5] Van Mansfelt. *Over de elasticiteit der spieren. Diss.* Utrecht, 1863.

[6] "Ueber Venen-elasticität." Ludwig's *Festgabe*, 1874.

[7] "Ueber Venen-elasticität." *Sitzber. d. Jenaischen Ges. f. med.- u. Naturwiss*, S. v. 6 Juli, 1877.

I have found for the longitudinal elasticity of the arterial wall would be, I believe, the hyperbolic parabola. But I am strongly inclined to think that the classing together, under some such name, of the different curves obtained, is more apt to mislead than to enlighten the ordinary physiological student.

I find that the elasticity curves of different arteries vary with the individual, with the species, with the age, with the nutrition, with absence or presence of disease, with the direction in which the strip of tissue is taken, &c., &c., and that in a manner which can be seen at a glance in most cases, and described as a rule without the use of x and y. The conclusion would seem to be that to seek to find the exact term which will express the form of the curve in all cases tends to lead us away from the points in which the curves differ from one another to those points in which they coincide—to lead us away from any points of practical importance, in fact, which may be learned from investigations on the elasticity of animal tissues.

IV. Elasticity of Moist Animal Tissues as Compared with that of Inorganic Substances.

Werthheim assumed that the asymptote of the curve of longitudinal elasticity of animal tissue corresponds to the first part of the curve of metals—that the molecular condition of animal tissues when stretched by relatively heavy weights is analogous, in so far as their elasticity is concerned, to that of metals when these were not stretched beyond the limits within which they follow Hooke's law.

My observations, referred to at the beginning of this paper, on the thermo-elastic properties of animal tissues have led me to consider the possibility that any relation which exists between the elasticity of animal and that of inorganic substances may be different from that supposed by Werthheim.

The case of caoutchouc appears to me of considerable interest in connection with this subject. We know from the observations of Horvath that the longitudinal elasticity of india-rubber is characterized by the fact that with relatively light weights the elongations increase more and more in proportion to the weights employed, so that the elasticity curve is at first convex towards the axis, and that it is only with heavier weights that the increments in length diminish in proportion to the weights used, the curve becoming concave towards the axis and ending in an asymptote.

From the experiments of Schmulewitsch[1], on the other hand, we know that the thermo-elastic properties of caoutchouc vary with the weights used. When stretched by relatively light weights he found that rise of temperature causes expansion, as in the case of the majority of other substances, and that it is only when heavier weights are employed that contraction results from warming it.

The natural conclusion would be that the molecular condition of animal tissues corresponds to that of caoutchouc when expanded by relatively heavy weights, since in both the elasticity curve and the thermo-elastic properties correspond.

Before accepting any such possibility I thought it desirable to find whether, on gradually increasing the weights applied to, *e.g.*, a strip of aortic wall, the curve continues asymptotic until the breaking point is reached.

It was possible that before this was arrived at the curve might perhaps become convex towards the axis. Such, however, is not the case. The curve continues asymptotic until rupture occurs.

With many metals the curve of longitudinal elasticity (on increasing the weights until the breaking point is arrived at) resembles, as Werthheim showed, that of caoutchouc, in so far that it is at first convex towards the abscissa, becoming with heavier weights concave on the same side. Should it be found that when stretched almost to the breaking point the thermo-elastic properties of these metals resembles that of animal tissues, the analogy of the molecular condition in the two cases, and the resemblance to that of caoutchouc when expanded by relatively heavy weights, would be complete.

The whole curve of animal tissues could then be held to correspond with that of metals when stretched to a point where their elasticity curve approaches the breaking point.

CONCLUSION.

A short reference to one or two of the facts contained in the foregoing pages, such as will indicate the scope of the paper, may not be out of place in concluding.

It has been pointed out that animal tissues differ from the vast majority of other substances in their thermo-elastic properties. They contract on

[1] *Loc. cit.*

being warmed and expand when their temperature is lowered. Corresponding with this we find that on being stretched their temperature rises, to fall again on their being relaxed.

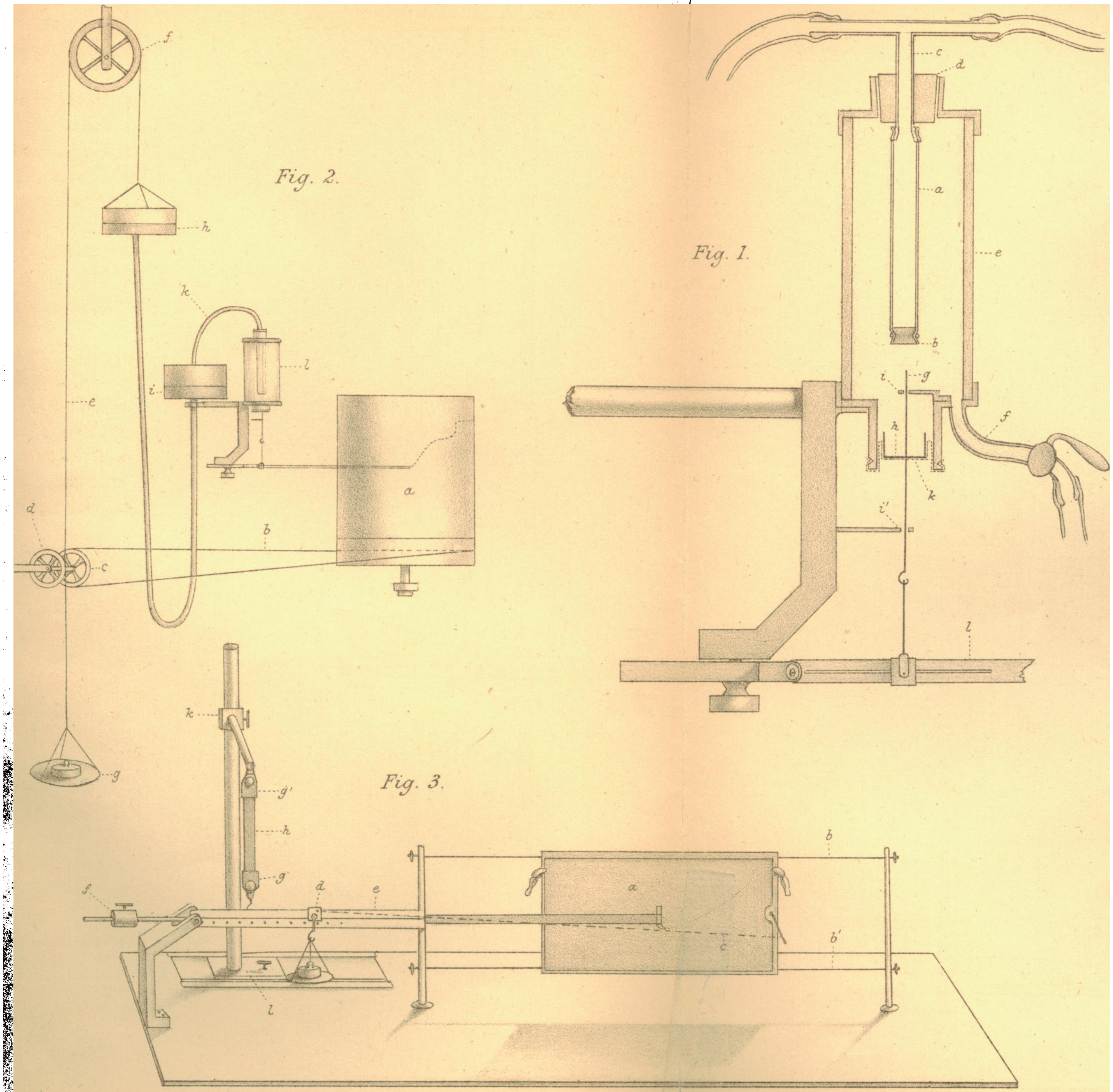
When we come to investigate the elasticity of the arterial walls we find that this is marvellously well adapted to the circumstances under which it comes into play in the living animal. Considered as tubes, it is found that the arteries are most elastic, most distensible, with internal pressures such as, during the life of the animal, have existed in their interior. As has been pointed out, the maximum increase in capacity with unit increase of internal pressure is reached, in the case of the aorta and large arteries of different species of animals, with a pressure at or near the medium blood pressure of the animal from which the specimen was taken.

As we have seen, in any given animal the ratio of increase of volume to increase of pressure is the same in the aorta and its branches. From a functional point of view the elasticity of the large arterial tubes is the same for each individual. On comparing the capacities when undistended with those when distended with a given internal pressure, it is found, however, that the relation is not the same for the aorta and its branches. The aorta is relatively wider in its undistended condition than the femorals and carotids.

The elasticity of the arteries is much more readily modified by diseases affecting the general nutrition than is usually imagined. As has been shown, slow febrile processes, producing marasmus, may modify completely the form of the curve of elasticity which is constructed by taking the cubic capacity of the piece of arterial tube as the ordinates and the internal pressures as the abscissæ. The relation of the pressures to the volumes of portions of aorta or artery from persons or animals which have suffered from some wasting illness, not specially affecting the arterial system, is quite different from that which exists in health. Where marked marasmus has existed before death the arteries are found to be relatively wider than normal, and are most distensible with internal pressures immediately above zero.

The effect of age on the elasticity of the arteries has been dealt with at some length. It has been shown that only in the case of young children do we find that the elasticity of the arteries is so perfectly adapted to the requirements of the organism as it is in the case of the lower animals.

It has been shown that the ratio of expansion of strips of the aortic wall to the weights employed to stretch them remains much the same



1/6 natural size.

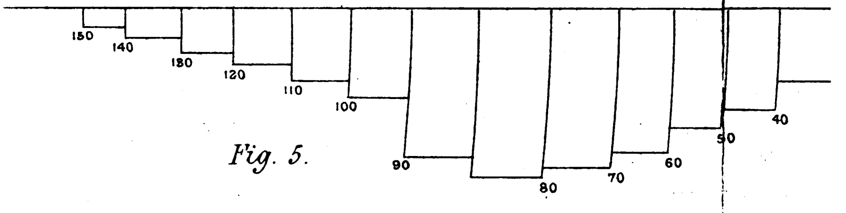


Fig. 5.

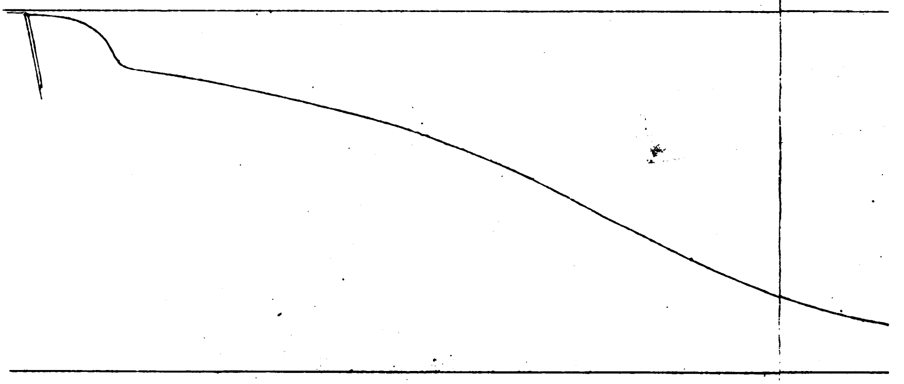


Fig. 8.

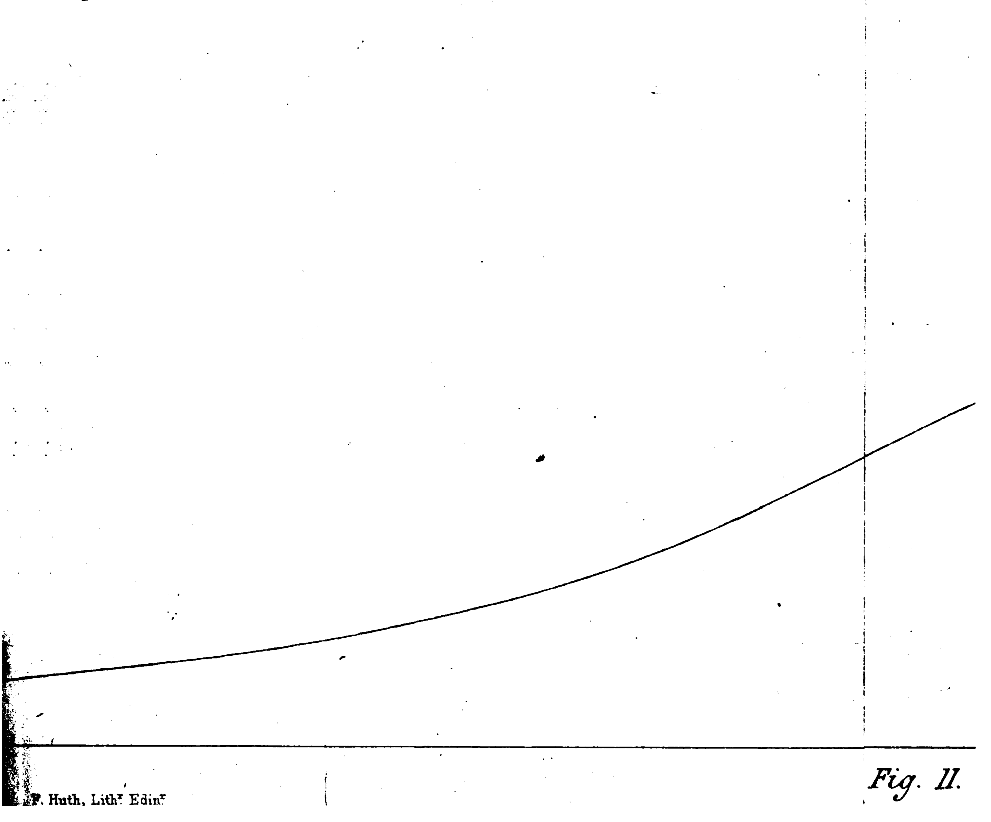


Fig. 11.

F. Huth, Lith^r Edin^r

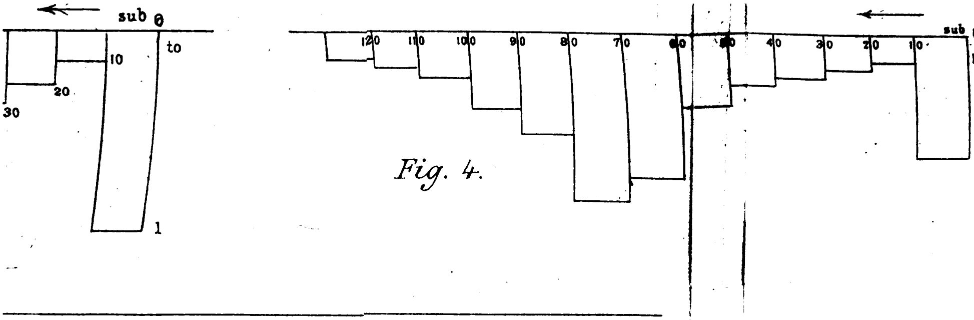


Fig. 4.

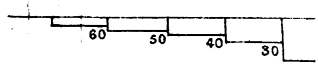
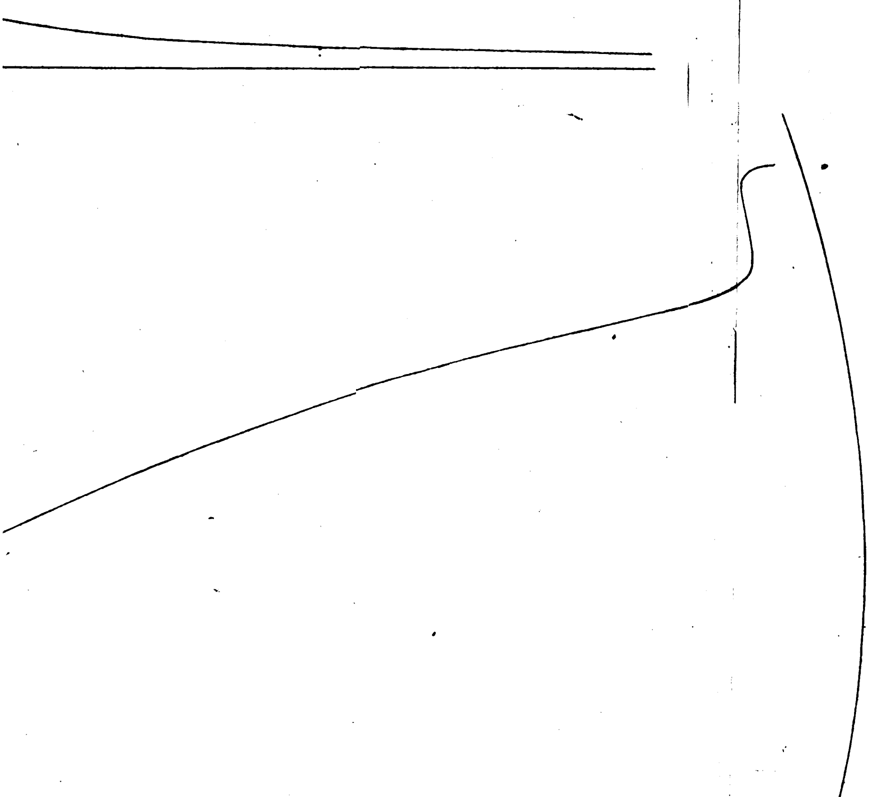


Fig. 6.



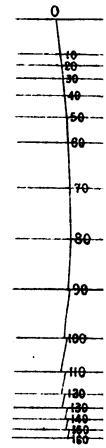
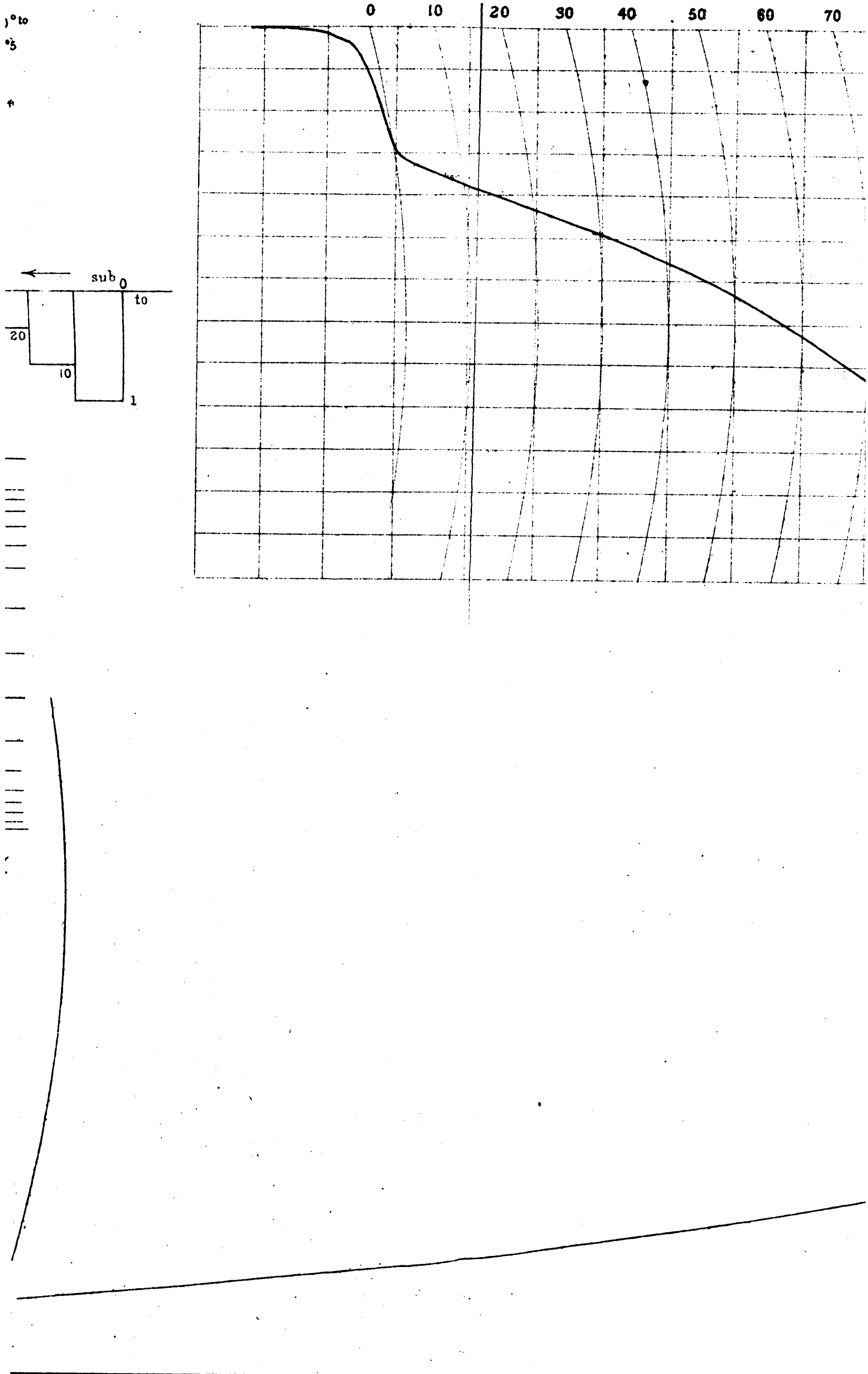


Fig. 7



Fi

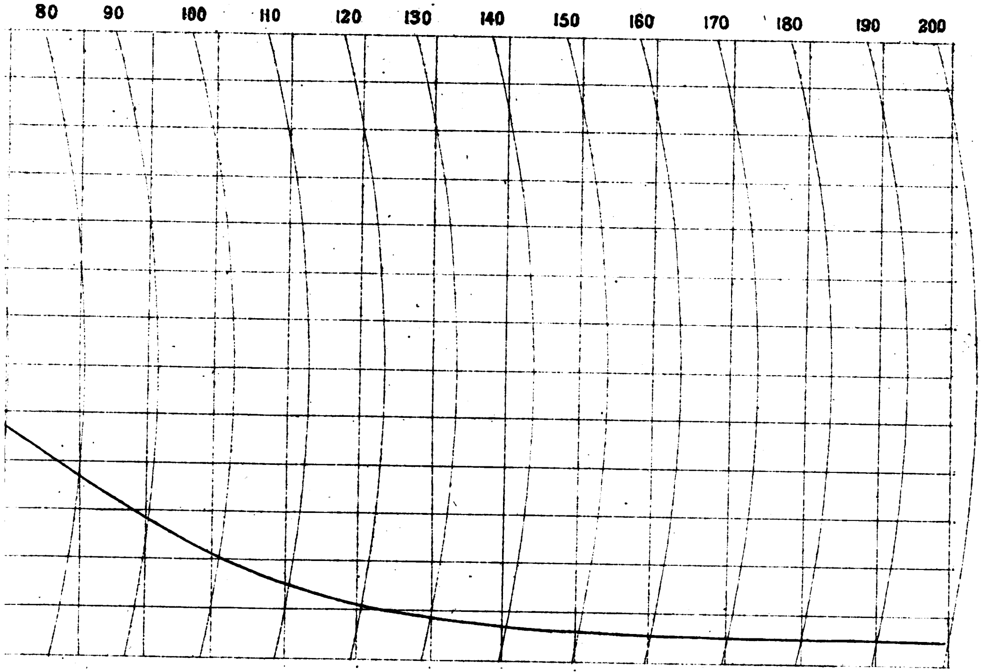
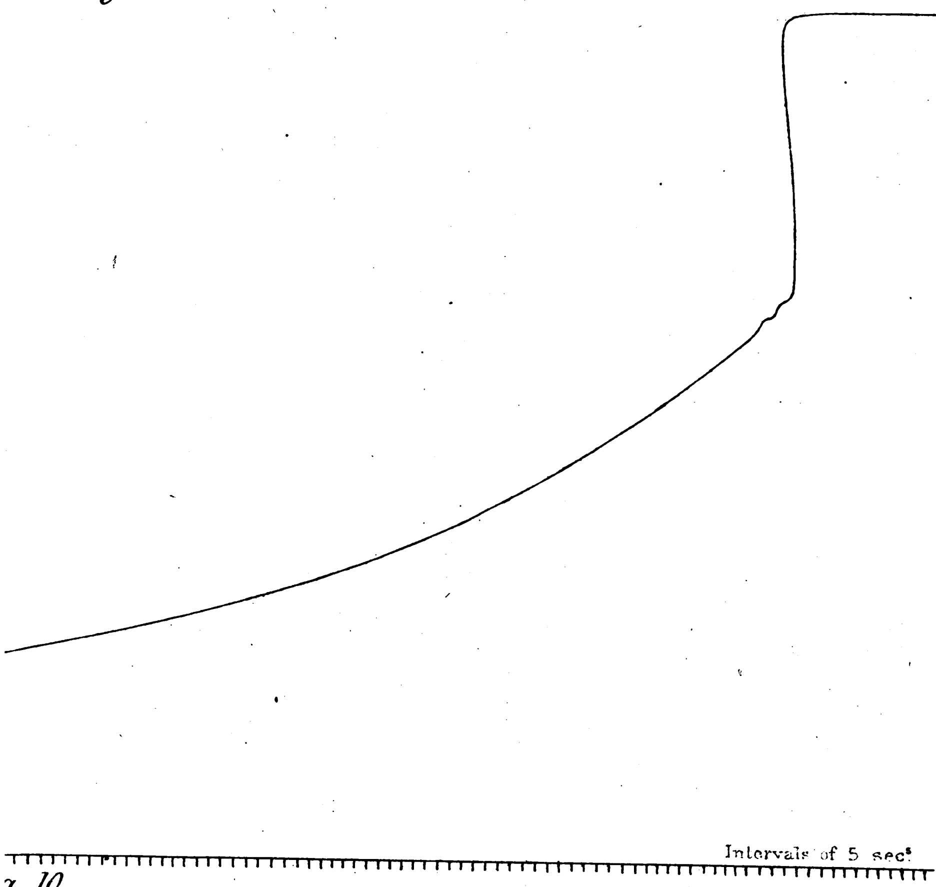

80
90
100
110
120
130
140
150
160
170
180
190
200

Fig. 9.


Intervals of 5 secs

g. 10.

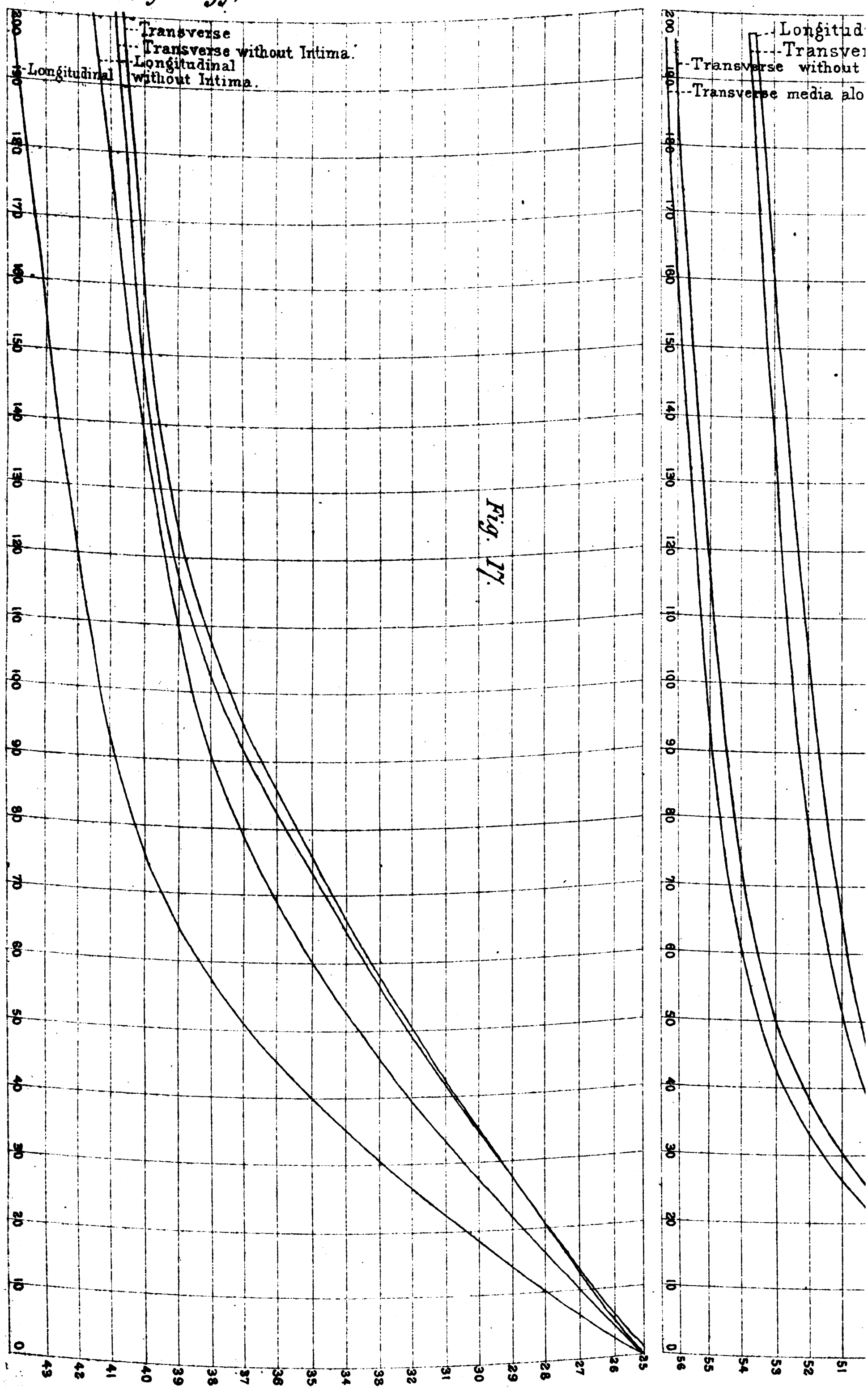
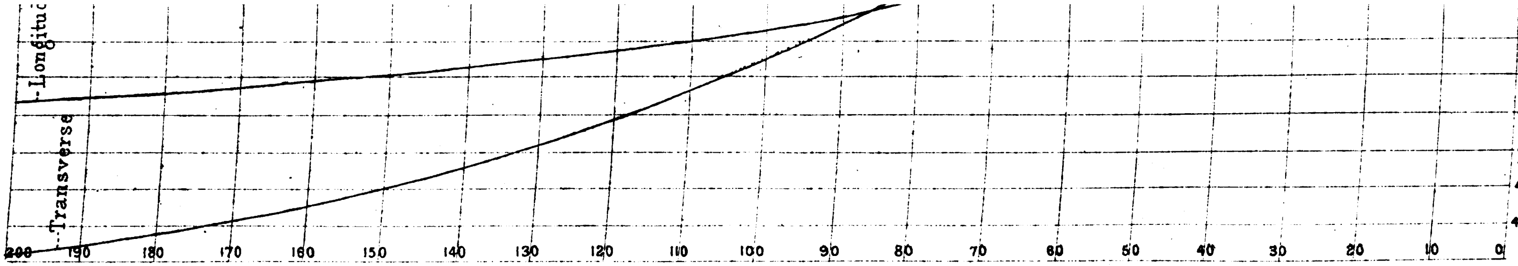
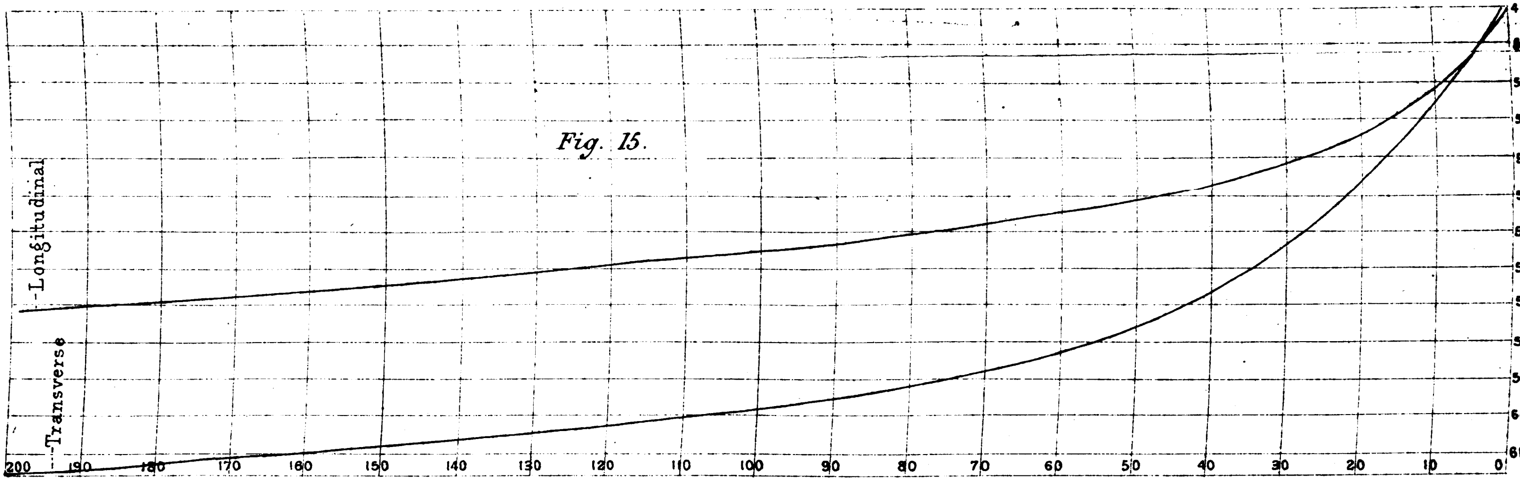

Transverse
Transverse without Intima.
Longitudinal
Longitudinal without Intima.
Longitud
Transver
Transverse without
Transverse media alo

Fig. 17.

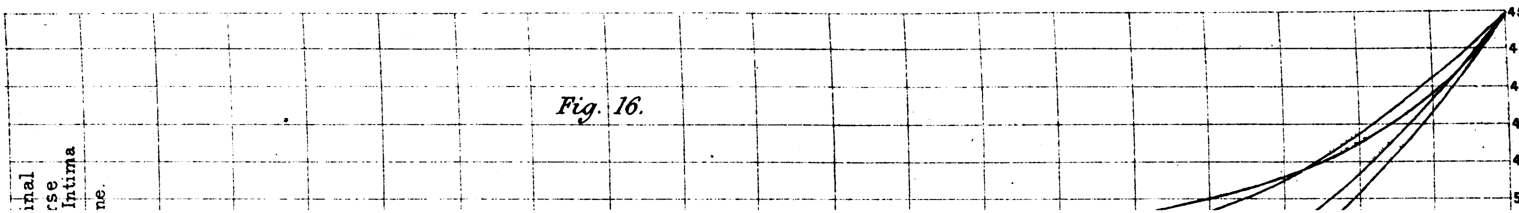


Longitud
Transverse



Longitudinal
Transverse

Fig. 15.



inal
rse
Intima
ne.

Fig. 16.

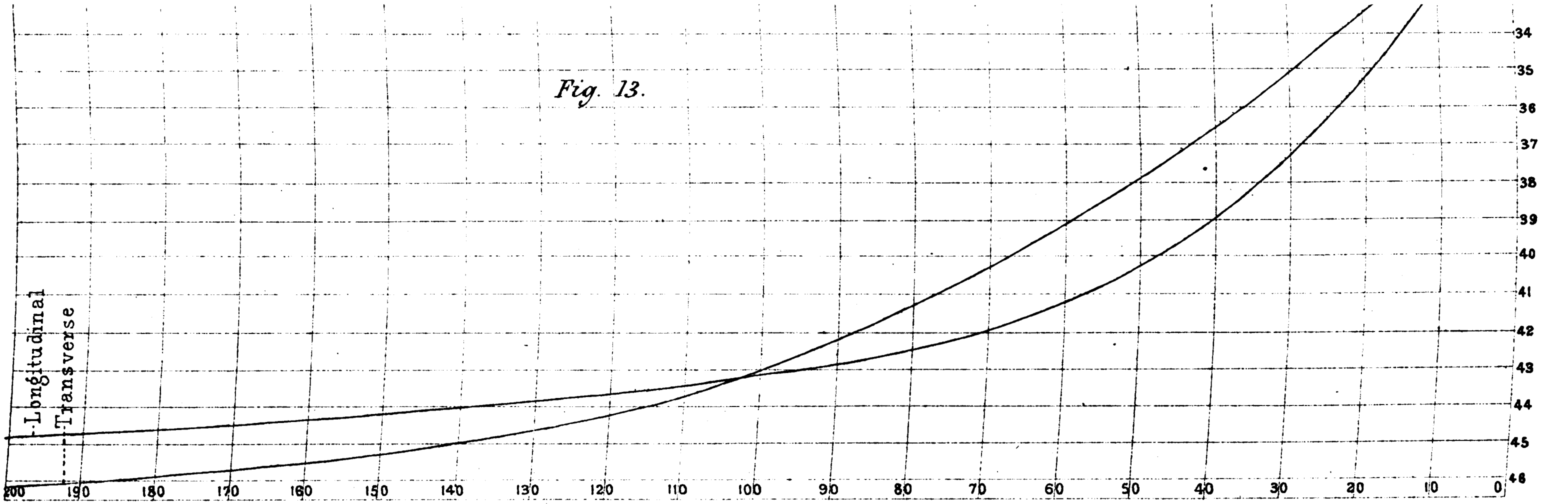

Longitudinal
Transverse
200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0
34 35 36 37 38 39 40 41 42 43 44 45 46

Fig. 13.

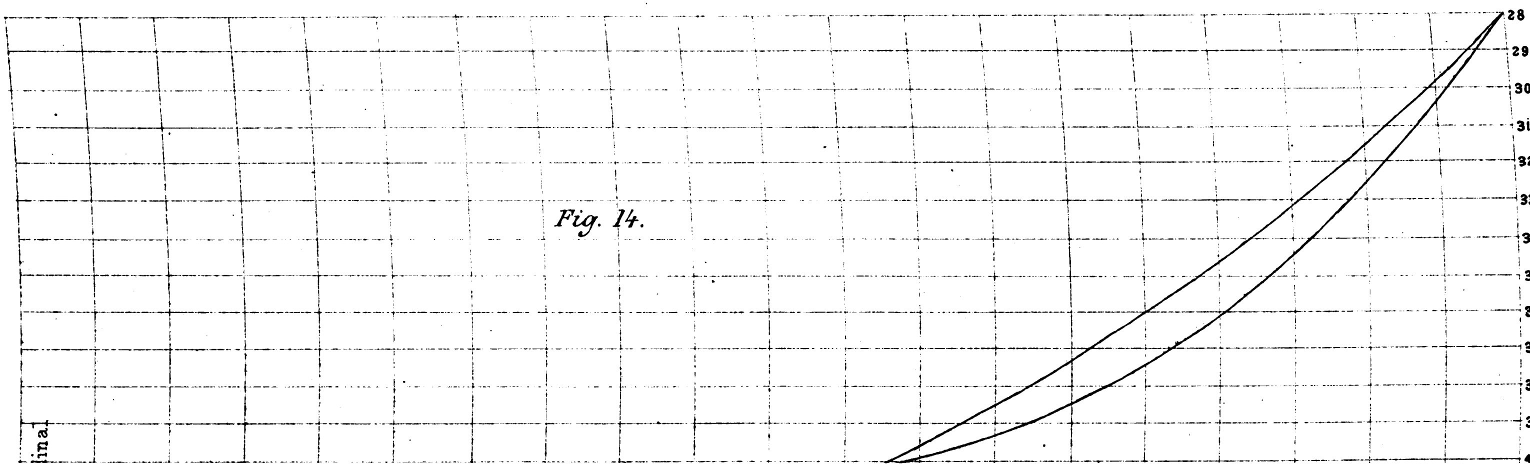

28 29 30 31 32 33 34 35 36 37 38 39 40

Fig. 14.

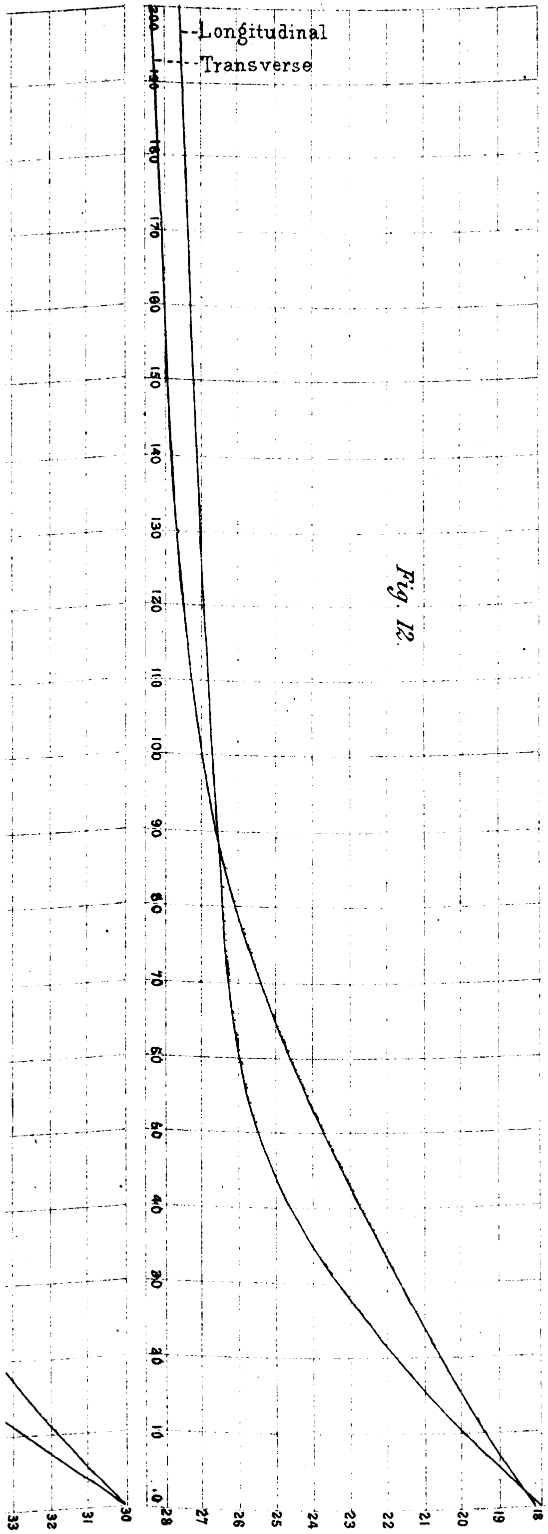


Fig. 12.

F. Huth, Lith^r Edin^r

from childhood up to a certain age. And from this it follows that the elasticity of the arteries, as tubes, will go on increasing until, with adult age, their full diameter is reached. With old age the elasticity of the arteries is found greatly modified in its characters, becoming less and less fitted to enable the arteries to fulfil their function in the economy.

I do not intend, however, to give a *resumé* of the contents of the above pages.

I have not, it may be added, sought to prove in the course of this paper that the elastic properties of dead arteries are closely allied, if not identical, with those they possess in the living animal.

There is no want of analogy in the case of other tissues, such as voluntary muscle, which might justify our assuming that death will not change to any important extent the physical properties of the arterial wall; but I prefer to leave this subject untouched, hoping to be enabled to obtain trustworthy data from experiments on the blood vessels of living animals.

In conclusion, it is my pleasant duty to express my warmest thanks to Professor Goltz for the assistance and advice with which he has furnished me in connection with this subject. To Professor v. Recklinghausen also, in whose institute a number of my observations were made, I have to express my grateful thanks.

CAMBRIDGE, *November*, 1880.

EXPLANATION OF FIGURES.

PLATE V.—Fig. 1, *vide* text, p. 133; Fig. 2, *vide* text, p. 136; Fig. 3, *vide* text, p. 146.

PLATE VI.—Figs. 4, 5, and 6 are sufficiently described in text, p. 134. Fig. 7 is from a portion of rabbit's femoral artery, taken with the instrument illustrated in Fig. 1. The short horizontal lines were drawn after successive increments of intra-arterial pressure. The figures give the intra-vascular pressure at the time that each line was drawn. The quantity of oil within the instrument remained the same during the time that the tracing was taken. Figs. 8 and 9.—The curved vertical lines of Fig. 9 give the correction for the lever, they being arcs of a circle whose radius is of the same length as the lever. The figures above the curve give the intra-arterial pressures in m.m. of mercury. The ordinates of the curves 8, 9, 10, and 11 are the cubic contents of the portion of artery, and the abscissæ are the intra-vascular pressures which increase in all at the same rate as in Fig. 9. In tracings 8 and 9 the intra-vascular pressure was *raised* from below 0 to 200, while in Figs. 10 and 11 it was *lowered* from 200 to below 0. In Figs. 10 and 11, therefore, the zeros of the abscissæ are at the right-hand side of the curves.

PLATE VII.—Sufficiently described in text.